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RESEARCH ON GASEOUS OPTICAL MASER TO DEVELOP HIGH CONTINUOUS WAVE POWER AT OPTICAL WAVELENGTHS

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ABSTRACT

He - Ne gas lasers at both 1.15μ and 6328A have been successfully operated during the past quarter. These lasers are of conventional design and the results have demonstrated the soundness of our apparatus and our fabrication techniques.

Detailed calculations indicate that the output power of a two region He - Ne laser may not be limited by He metastable-metastable ionizing collisions for levels up to about two orders of magnitude higher than are available from conventional gas lasers. The limiting level will be even higher if the cross section is smaller than the pessimistic value assumed in the calculations. The results of further design calculations are also included in this report.

Fabrication techniques for a gridded laser tube have been largely developed, and construction is proceeding.

Another scheme for achieving higher output powers has been considered, but it poses some practical problems. The two-region laser still seems to offer more promise than any other type of gas laser.

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INTRODUCTION

During this quarter, most of the effort was expended on assembly and operation of gas lasers of conventional type in order to familiarize ourselves with their characteristics and to insure the adequacy of our apparatus for later use. Some consideration was given to another possible method of increasing the output power from He - Ne gas lasers, but it was found to have disadvantages with respect to the gridded design which we have been pursuing. Detailed design and operating considerations for our gridded tube will be discussed below, as well as our experimental progress.

ANOTHER METHOD FOR ACHIEVING HIGHER OUTPUT POWERS

In the He - Ne laser, the major problem is to reduce excitation to the Ne 2p level by inelastic collisions between electrons and Ne ls metastable atoms. (For the recently announced 3s → 3p laser transition at 3. 39 microns, the problem will be to reduce excitation to the 3p level.) This excitation may be reduced either by reducing the electron concentration in the emission region (the basis of the two region laser) or by reducing the Ne ls metastable concentration. Since the primary destructive process for Ne ls metastables is by de-excitation at the walls, the concentrations can be reduced by increasing the surface area in contact with the Ne gas. The surface area can be increased by filling the laser tube with many tubes or rods as shown in Fig. 1, such that laser action could occur in the interstices and tube interiors. Such a geometry would require plane parallel rather than spherical confocal mirrors.

The single pass gain along a given path in the discharge is inversely proportional to the transverse dimension of that path. Furthermore, in order that the entire laser will oscillate coherently, the transverse dimensions of the interstice must be small enough so that the diffraction spread beam, after being reflected from an end mirror, will extend over several of the openings. For convenient laboratory mirror spacings, a reasonable interstice transverse dimension is about 0. 1 min.

The major difficulty with this scheme is the problem of obtaining uniform electrical discharges along the many possible current paths. Because of the nonlinearity of the resistances presented to the power source by the discharge paths, most of the excitation power will tend to concentrate in one or a few of the many possible paths. This problem is severe enough that we have not considered this method any further.

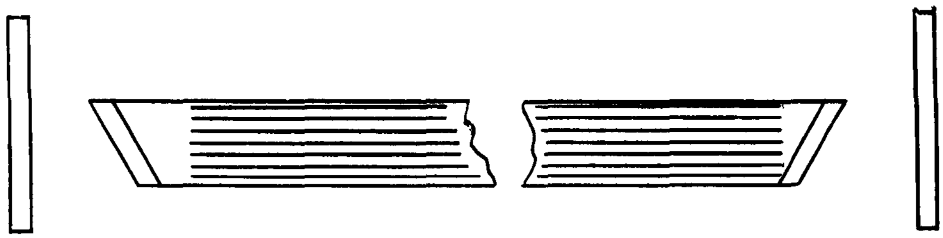

Fig. 1a - Laser using many internal tubes or rods, Brewster angle windows, and planc parallel mirrors.

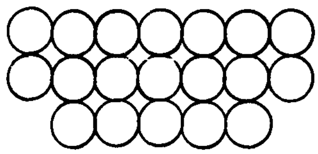

Fig. 1b - Enlarged end view showing loose packed array of quartz rods. Laser action would occur in the interstices.

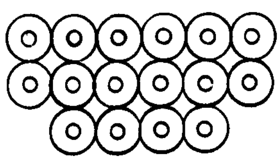

Fig. 1c - Enlarged end view showing loose packed array of quartz tubes. Laser action occurs both in the interstices and in the tube interiors.

DISCUSSION OF TWO REGION LASER OPERATION

We now discuss in more detail than in Interim Engineering Report No. 1 the characteristics of the emission region of a two region laser. We assume the geometry of our gridded tube, i.e., a discharge in an outer annular region and laser action in the central region, as shown in Figure 2. The concentration of He metastables is also shown schematically in the Figure. We shall concern ourselves with the details of only the central, emission region, for $r \leq R_1$. In this region the following diffusion equation applies:

$$D\nabla^2 H - H\, N < \sigma_{HN}\, v > = 0 \tag{1}$$

where
- D = diffusion constant for He ^3S atoms
- H = concentration of He ^3S atoms
- N = concentration of Ne ground state atoms
- σ_{HN} = cross section for excitation to the Ne 2s state by collision with a He ^3S atom
- v = relative velocity of He ^3S and Ne ground state atoms

The brackets in the second term indicate an average of the product over all velocities. Terms neglected here are contributions by He ^3S - He ^3S ionizing collisions, He ^3S - Ne 1s ionizing collisions, and effects of residual elections in the emission region. The first and last of these may be significant in some cases and will be discussed later. The second is not expected to be important because of the relatively small density of Ne 1s atoms.

For cylindrical symmetry, the solution of Equation (1) is

$$H = H_o\, I_o \left(\left[\frac{N}{D} < \sigma_{HN}\, v > \right]^{\frac{1}{2}} r \right) \tag{2}$$

where H_o is the density at the radius $r = 0$.

In Equation (2), I_o is a hyperbolic Bessel function of the first kind of zeroth order which behaves much like an exponential. For a Ne pressure of 0.1 mm of Hg, Ward has calculated[1] the value of $N < \sigma_{HN}\, v >$ to be 18×10^3 sec $^{-1}$. The value of D is known to be 470 cm^2/sec. Thus we have

[1]Roy C. Ward, Technical Report No. TDR (2250-20) TN-1, Aerospace Corporation, El Segundo, California; available as ASTIA Document No. 265059.

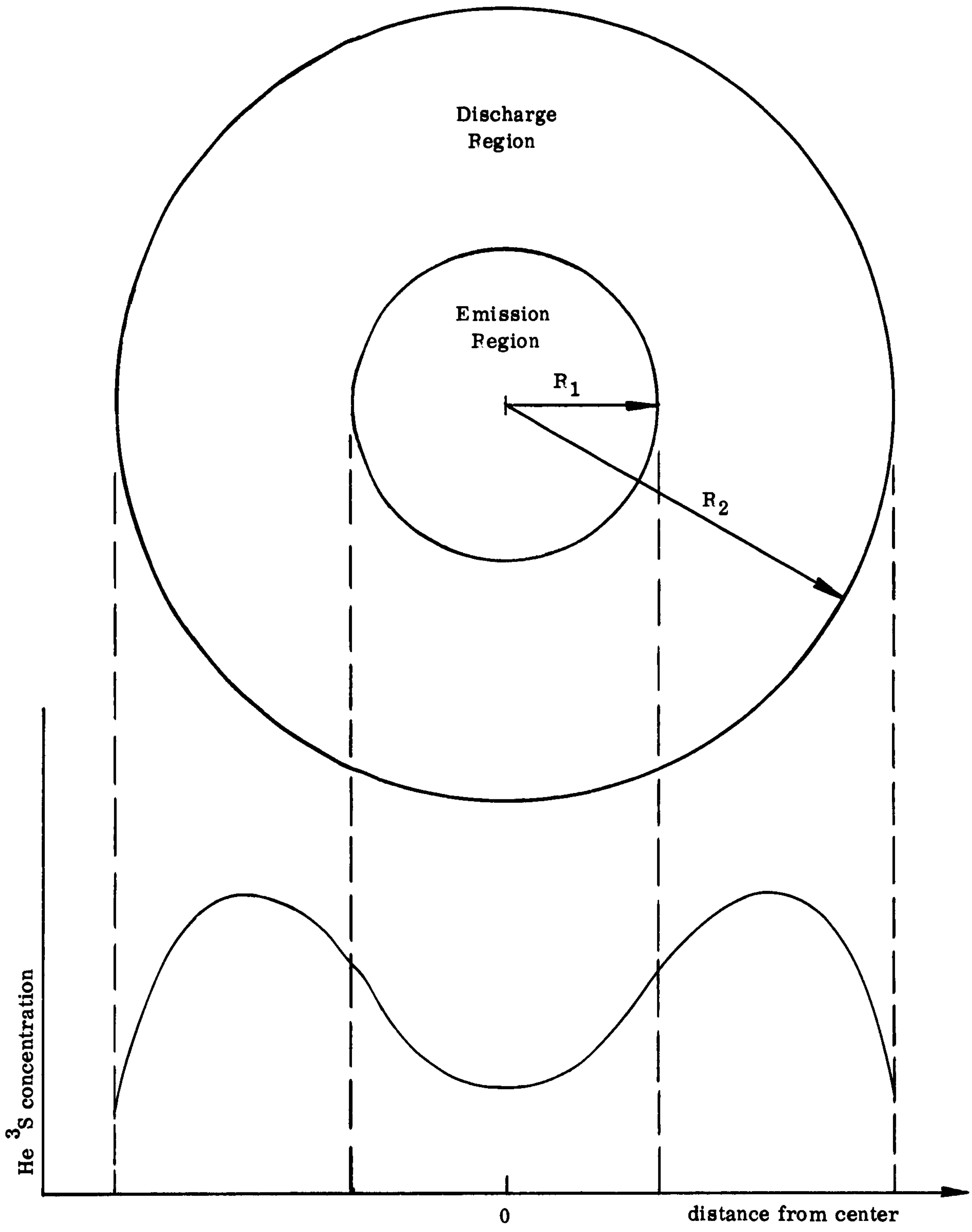

Fig. 2 - Top - Cross section of two region laser.
Bottom - Schematic illustration of variation of He ^{3}S concentration across the tube diameter.

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$$H = H_0 \, I_0 \, (6.2\, r) \qquad \text{c.g.s} \tag{3}$$

for the concentration of He metastables in the emission region. For our design value of $R_1 = 0.32$ cm, the ratio of the value of H at $r = R_1$ to that at $r = 0$ is 2.3. The value of H increases roughly exponentially from $r = 0$ to $r = R_1$. Since the total variation in He metastable concentration across the emission region is only about a factor of two, the average concentration in the emission region will be only slightly lower than the average concentration in the discharge region, $R_1 \leq r \leq R_2$. Thus, for comparable discharge conditions in the two-region laser and a conventional gas laser, we expect comparable output powers.

Equation (1) neglects ionizing collisions between He metastables. To account for them, the term $-H^2 < \sigma_{HH} v >$ must be included in Equation (1), where σ_{HH} is the cross section for ionizing collisions. However, such a term makes the equation nonlinear, and it must then be solved numerically. We can estimate the importance of that term by calculating the density H at which the term becomes comparable to the second term in Equation (1), i.e., when

$$H \sim \frac{N < \sigma_{HN} v >}{< \sigma_{HH} v >} \tag{4}$$

The value of σ_{HH} is unknown, but has been estimated by Ward[1] to be less than 10^{-15} cm^2. Assuming a value of 10^{-15} cm^2 for it, and using the room temperature velocity v of 1.4×10^5 cm/sec and a value of N for a Ne pressure of 0.1 min of Hg, we obtain

$$H \sim 1.3 \times 10^{14} \text{ cm}^{-3}$$

This is roughly two orders of magnitude larger than the estimated value of the He metastable concentration in a conventional laser[1]. Thus we expect He ^3S metastable-metastable ionizing collisions to limit the output power of two-region lasers at a level roughly two order of magnitude greater than that obtainable from conventional lasers.

The previous discussion has been exclusively concerned with the Ne $2s \rightarrow 2p$ transition at 1.15μ which is enhanced by the presence of He ^3S atoms. It is not wholly applicable to the Ne $3s \rightarrow 2p$ and $3s \rightarrow 3p$ laser transitions at 6328 A and 3.39μ respectively, which are enhanced by the presence of He ^1S metastable atoms. The various cross-sections and diffusion constants for the latter processes are unknown, so we are unable to estimate the effects of ionizing collisions between He ^1S metastables.

We now turn to a discussion of the electron density as a function of radius in the two-region laser. Figure 3 depicts schematically the way in which the potential will vary as a function of radius.

In (3a), the grid is floating and assumes the wall potential. In (3b), a negative dc bias is applied to the grid in order to decrease still further the number of electrons in the emission region. The plasma potential assumed in the discharge region is V_o, that in the emission region is V_1. If n_o is the election concentration at the plasma potential V_o in the discharge region, then the concentration at the potential V_1 in the emission region is

$$n_1 = n_o \exp\left[-\frac{e(V_o - V_1)}{k\,T}\right]$$

where T is the electron temperature. A typical value of kT for a conventional He - Ne laser is roughly 16 ev. If this value of kT is assumed, then we have the following values of $\frac{n_1}{n_o}$ for corresponding values of e $(V_o - V_1)$:

$\frac{n_1}{n_o}$	$e\,(V_o - V_1)$ (ev)
0.1	37
0.01	74

Since V_1 will be somewhat higher than the grid potential, we see that (if V_G is the grid potential) the values of e $(V_o - V_G)$ must be larger than the given values of e $(V_o - V_1)$ in order to maintain values of $\frac{n_1}{n_o}$ as small as those given. The value of $(V_o - V_1)$ for a floating grid will be in the neighborhood of 20v, so it will be necessary to provide a dc bias on the grid in order to maintain low values of electron concentration in the emission region.

Reference electrodes in contact with the discharge are necessary in order to establish a reference voltage level with respect to which a grid bias is to be maintained. Since the dc current collected by the grid (negative with respect to the wall potential) will be supplied almost entirely by ions, and that collected by the reference electrodes (positive with respect to the plasma potential) will be supplied mostly by electrons, the ratio of the current densities to the grid and reference electrode will be given by the ratio of random ion and electron velocities. In

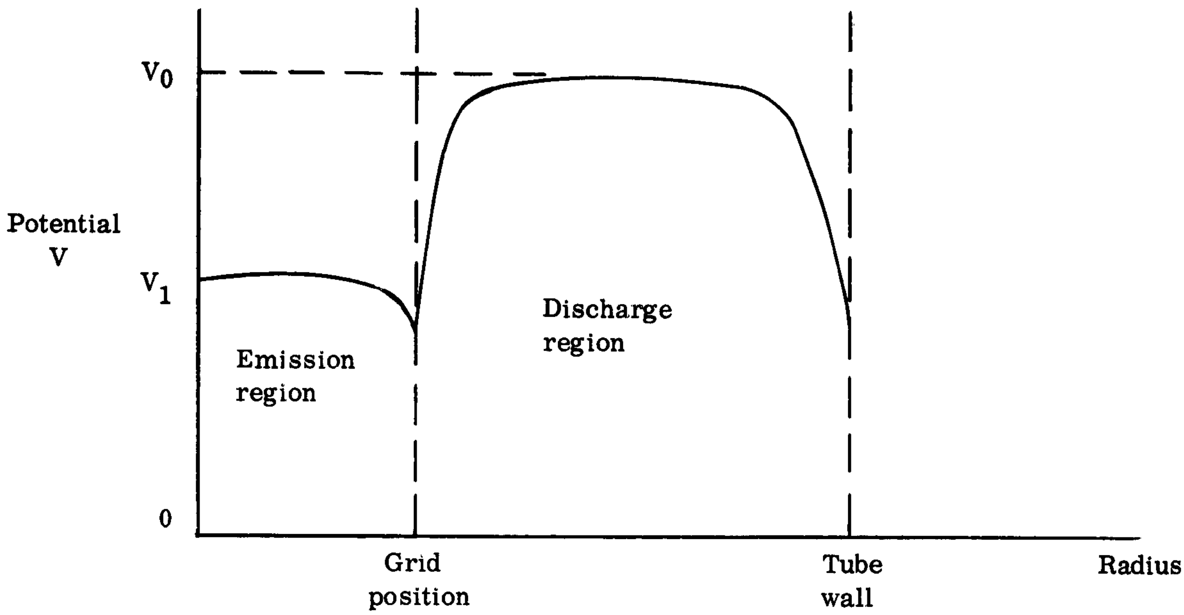


Fig. 3a - Potential as a function of radius for grid floating

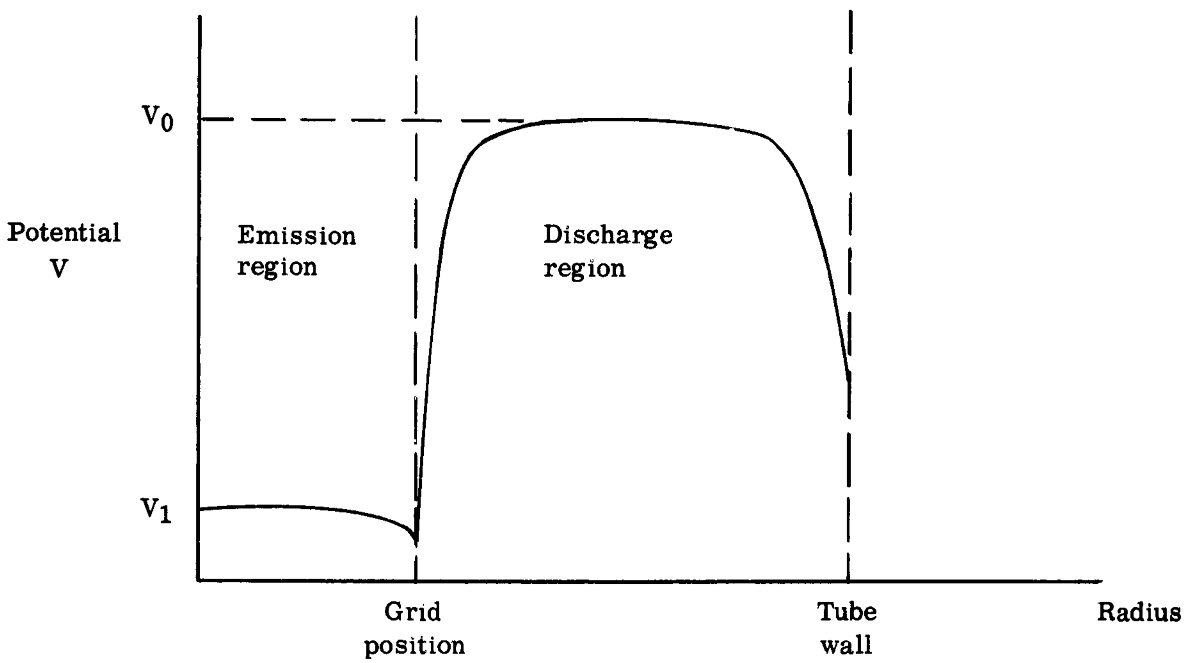


Fig. 3b - Potential as a function of radius for grid with dc bias calculating this ratio we assume that most of the ions are Ne ions with a temperature of about 400^{o} K, and that the electrons have an average thermal energy of about 20 ev. For such a case, the ratio of current densities will be approximately 2×10^{-4}. This means that the reference electrode surface area need only be a factor of 2×10^{-4} times that of the grid. Such a reference electrode will make possible arbitrary values of the grid bias, and thus will allow arbitrarily small electron concentrations in the emission region.

DESIGN OF GRIDDED TUBE

Over-all Construction

Figures 4 and 5 are sketches showing construction details of the gridded laser tube. The entire tube will be about 26 inches long and the main envelope will be quartz tubing, precision-shrunk to 3/4 inches I. D. The Brewster angle windows are 3 inches in diameter, 1/4 inch thick quartz disks, flat to 1/10 wave length. The grid is fabricated from sheet molybdenum mesh 0. 001 inch thick, with a square grid of 0. 001 inch diameter wires separated by 0. 0035 inch. The mesh was photoetched from solid sheet molybdenum by Buckbee-Meers Co. It is formed into a cylinder by wrapping around a 1/4 inch diameter mandrel and spot-welding a seam. The molybdenum shorting rod, used to reduce the electrical resistance of the grid, is spot-welded along the seam. The grid will be supported in the tube by means of quartz spacers drilled from quartz plates. The grid and reference electrode leads will be brought out through glass seals which will be attached to the quartz tube.

Design Considerations

The diameter of the grid was chosen as a compromise between minimizing the variation in excitation density over the cross section (discussed above in "Discussion of Two Region Laser Operation") and maximizing the total active volume. The mesh size of the grid was chosen to be comparable with the Debye length in a plasma containing an electron concentration n of 10^{11} to 10^{12} cm^{-3} and an electron temperature T about 2×10^{5} deg K.

Because of the low resistance presented by the discharge, the grid must be also designed for low electrical resistance. The purpose of the shorting bar spot-welded to the grid in Figures 4 and 5 is to reduce the grid's electrical resistance to a value less than that of the discharge. The grid will be about 46 cm long, leading to a discharge impedance of about 1/2 ohm, and a grid resistance (with a shorting bar 1/16 inch diameter) of about 1/5 ohm. A longer grid than this would lower the discharge impedance and raise the grid resistance so that too large a fraction of the rf power would be dissipated in the grid.

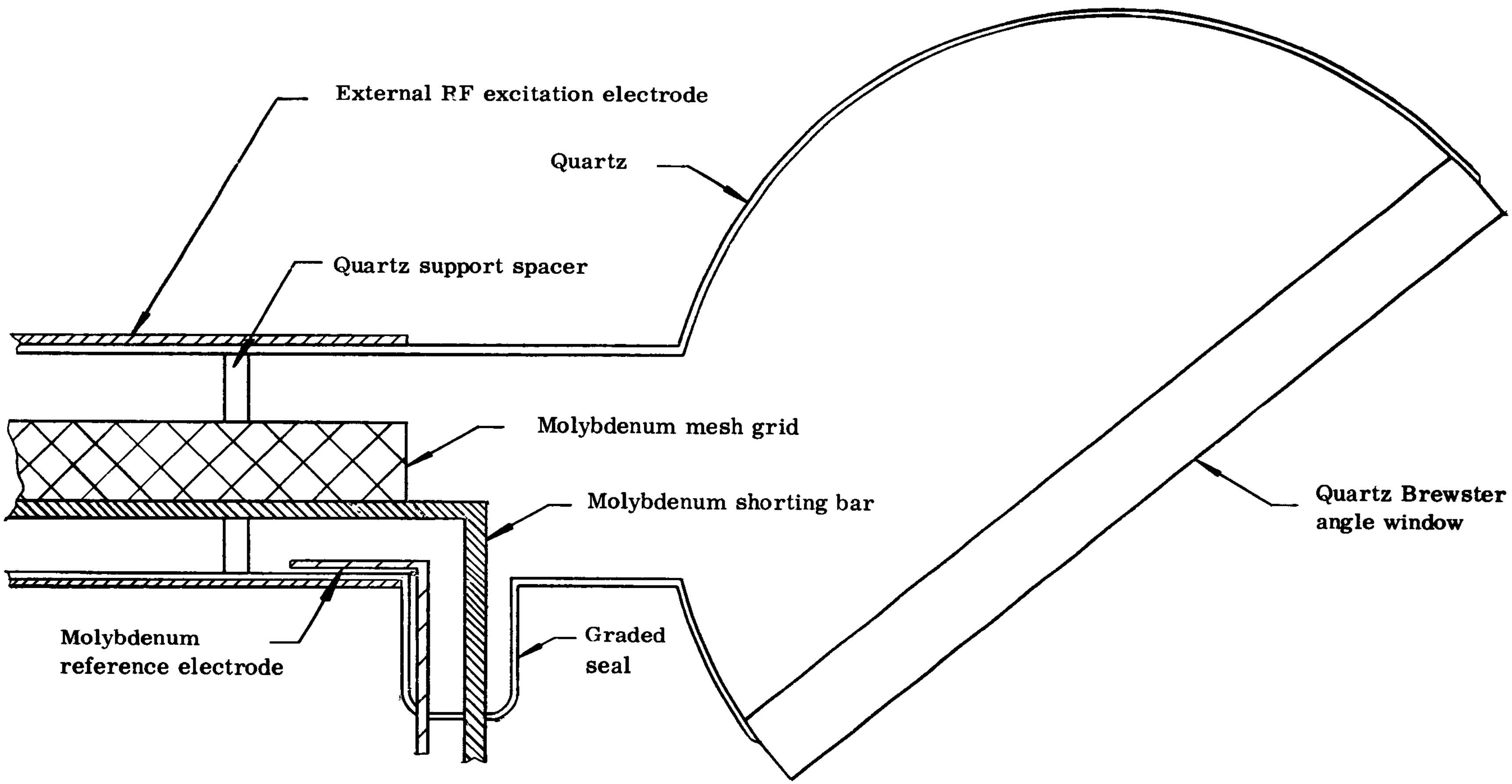


Fig. 4 - Diagram indicating the construction details of the gridded laser tube. Scale approximately two times actual size.

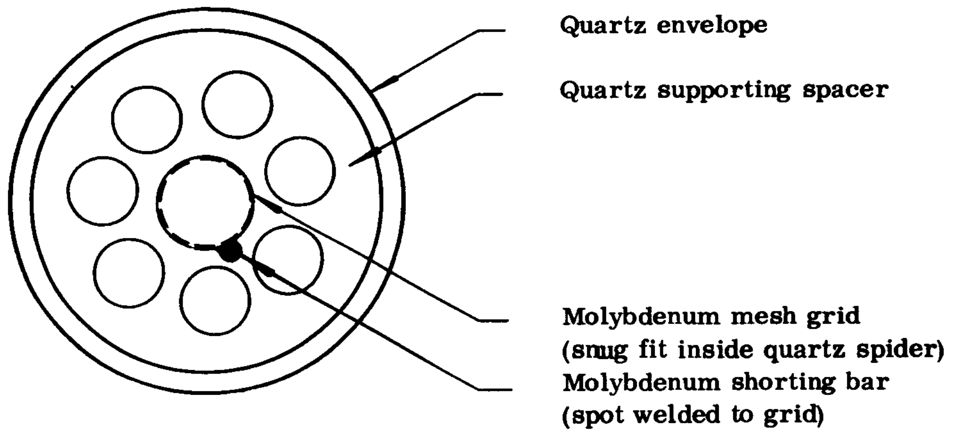


Fig. 5 - Cross section of gridded laser tube showing support spacer for grid.
Scale two times actual size.

The grid must also be designed to withstand moderately high operating temperatures. Most of the power delivered to the discharge will ultimately be transferred to the surfaces in contact with the discharge. If most of the power is transferred to the walls by ambipolar diffusion and recombination, then the grid plus surrounding sheath can be considered a solid collecting surface for electron-ion pairs, and, for our geometry, about 1/4 of the total power delivered to the discharge will be transferred as heat to the grid. A solution of the heat flow equation for our geometry then indicates that the grid will be hotter than the tube wall by about 2.3 deg. C for every watt of power transferred to the grid. Thus, if a total of 600 watts is delivered to the discharge, about 150 watts will be transferred to the grid, and the grid temperature will be about 350 deg. C higher than the tube wall temperature.

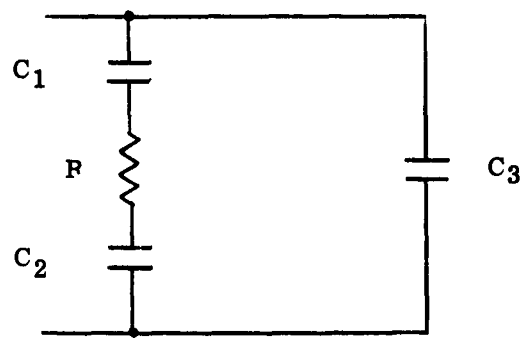
The rf power must be delivered to an impedance of an ohm or less, thus necessitating an impedance matching circuit. The equivalent circuit of the gas discharge tube can be approximated by the circuit shown in Figure 6a. R is the resistance presented by the electrons in the discharge, C_1 is the capacity between the external electrode and the discharge, C_2 the capacity between the discharge and the grid (which are separated by the sheath), and C_3 is the capacity present between the external electrode and the grid when there is no discharge present, i.e., when $R = \infty$. Figure 6b shows an inductance L used to resonate with the capacity in the laser tube, in order to increase the impedance presented to the rf transmitter.

COMPLETED EXPERIMENTAL APPARATUS

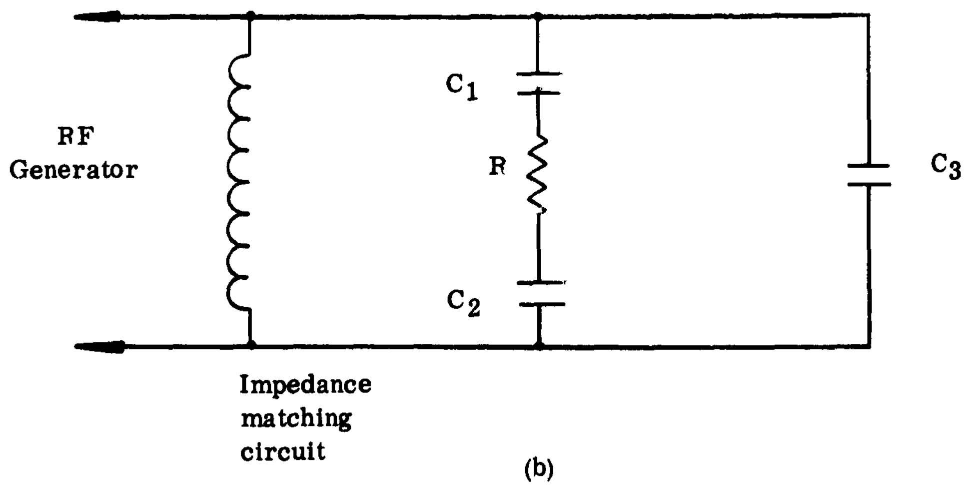
Optical Bench and Mirrors

An optical bench constructed according to the sketches shown in Interim Engineering Report No. 1 is shown in Figures 7 and 8. Two steel end plates hold mirror mounts hung from single steel torsion rods. The end plates are mounted on a 48 inch long, 3 inch O.D., 2 1/4 I.D. invar tube. Each mirror mount pivots on its torsion rod by adjustment of three micrometer screws. The laser tube is supported in asbestos cradles mounted in steel carriers which can be adjusted to arbitrary positions on the invar tube.

The mirrors are made from optical quality fused quartz, and have multiple layer dielectric coatings peaked for maximum reflectivity at the operating wavelength. The mirrors are 2 in. diameter, 1/2 in. thick, with a 1 meter radius of curvature. Regularity of the spherical surfaces is 1/20 wavelength, the other surfaces are flat to 1/10 wavelength. Two pairs of mirrors are presently being used -- one has 0.3 percent transmission at 1.15μ, the other has 0.1 percent transmission at 6328A.



(a)



(b)

Fig. 6 - (a) Equivalent circuit of laser tube. (b) Impedance matching circuit connected to laser tube.

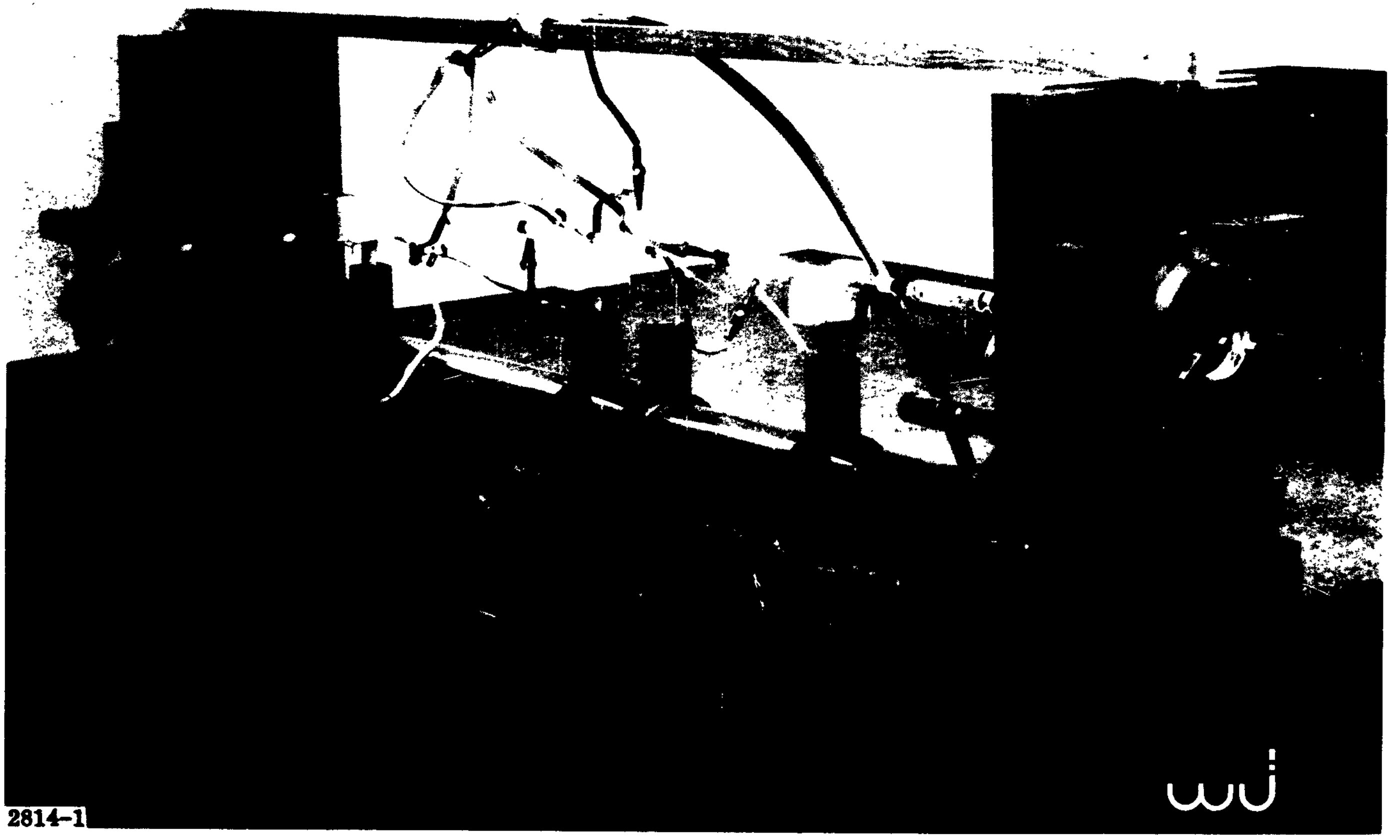


Fig. 7 - Photograph of gas laser apparatus showing optical bench and laser tube.

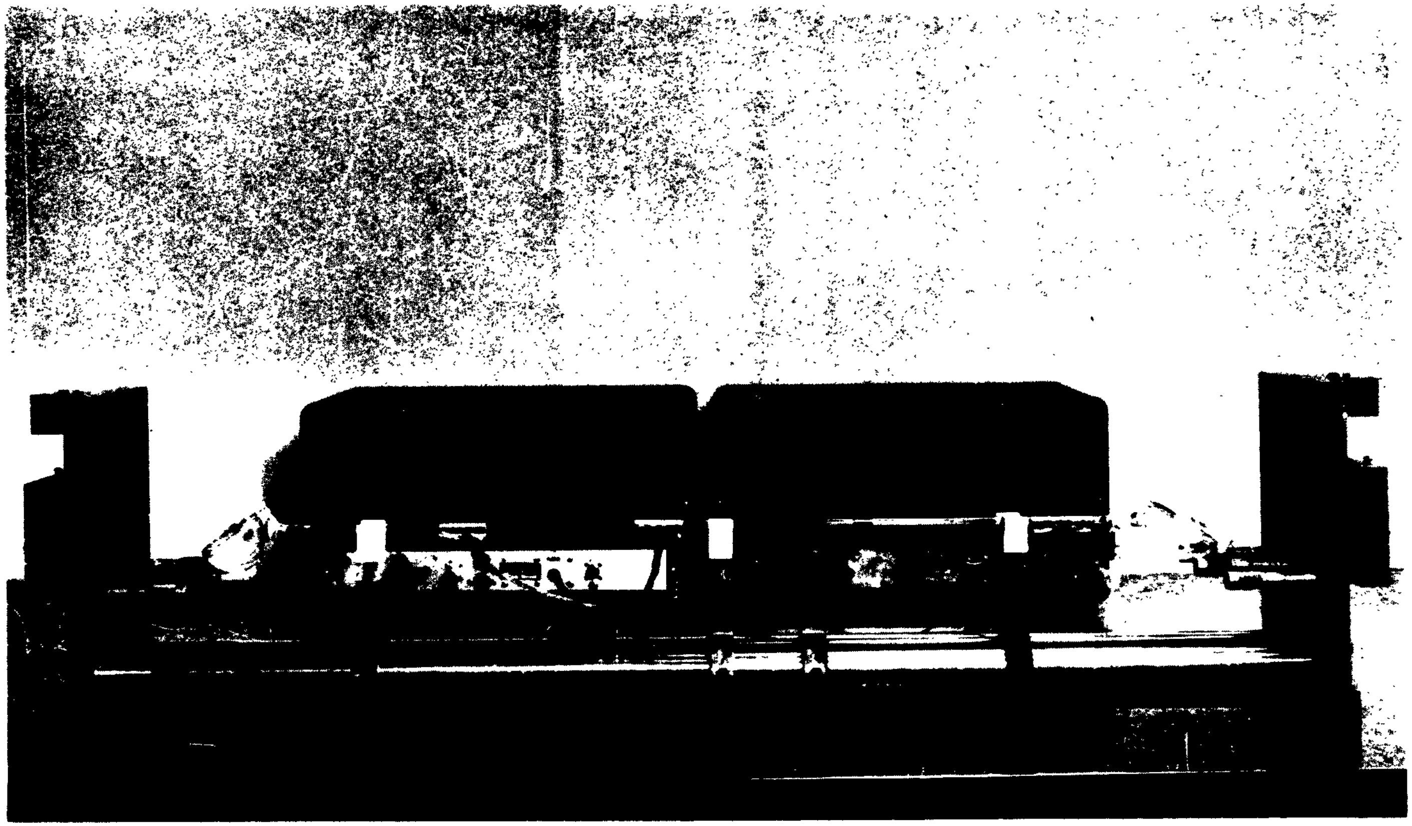


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Fig. 8 - Photograph of gas laser apparatus showing optical bench, and laser tube.

Laser Tubes

Two laser tubes have been constructed and operated. Both were of conventional design. The first (shown in Figure 7) consisted of 7 mm I. D. quartz tubing with quartz-to-glass graded seals on the ends, and Brewster angle windows of 2 in. diameter 7056 glass. The windows are not optically flat -- they are polished disks purchased from Ednalite Corp. and are ordinarily used for windows in television optics. However, they performed well in this application also. This tube was operated both at 1.15 μ and 6328A. Subsequently it was broken, however, and has not yet been repaired.

The second tube was constructed entirely of quartz, but otherwise is similar to the first tube. The Brewster angle windows are 3 in. diameter, 1/4 in. thick disks with surfaces flat to 1/10 wavelength and parallel to 1 second of arc. The orientation of the windows is accurate to about 1/2 degree. This tube has operated at 1.15 μ but not at 6328A due to a slight fogging of one of the windows. This fogging is believed to be due to devitrification of the fused quartz during the process of sealing the windows onto the tube.

Fabrication techniques for the grid and its supports, for the gridded tube, are presently being developed. Presently flat pieces of mesh, six inches long, are being rolled onto an aluminum mandrel and spot-welded into a cylinder. The mandrel will be subsequently etched away and the grid sections fired at about 1000 deg. C in a wet hydrogen atmosphere. It is presently planned that the six inch long cylindrical grid sections will then be spot-welded to the shorting bar and to each other on a graphite mandrel, then slipped on to a molybdenum mandrel for a second firing and stress relieving.

Quartz spacers to support the grid in the center of the 3/4 in I. D. quartz envelope will be ground from disks cut from a 3/4 in diameter quartz rod. The spacers will be sealed into position in the envelope and the grid subsequently slid into position.

EXPERIMENTAL RESULTS

Relative laser outputs at 1.15 μ are measured with a PbS cell. Visual observations are made with the aid of a U.S. Navy surplus snooperscope. Absolute measurements have not yet been made, but an Epley thermopile is on order for this purpose. The maximum power output as determined by the PbS cell and the sensitivity curves supplied by Kodak is a few tenths of a milliwatt. The accuracy of this type of measurement is not good, however. The outputs of the first and second tubes were about the same at 1.15 μ.

The output of the first tube in the visible (6328A) has been photographed, and Figure 9 contains pictures of several of the mode patterns that we have observed. The figure shows the lowest and first order modes as well as several higher order modes.

CONCLUSIONS

Further detailed calculations indicate that He metastable-metastable ionizing collisions may not limit the output power of a two-region laser for levels up to about two orders of magnitude greater than are presently obtainable. In order to maintain a low electron density in the emission region it appears to be necessary to bias the grid negatively with respect to reference electrodes which must be included in the tube. Detailed calculations are possible only for the 1.15 μ output of the He - Ne laser, but two-region operation should be effective for the other two wavelengths also.

The two-region laser still appears to be the most promising type of laser for increased power output.

The optical bench, rf excitation apparatus, and associated experimental apparatus have proved satisfactory for gas laser use and should all be applicable to the operation and measurements of the characteristics of the two-region laser.

RECOMMENDATIONS

Work should continue on design and construction of a gridded laser tube as the best solution to the problem of increasing the power out of gas lasers.

Fig. 9 - Photograph of the gas laser output at 6328A. The laser beam impinged directly on the camera film with no intervening lenses.